Visakhapatnam Chapter

Proceedings of Indian Geotechnical Conference 2020
December 17-19, 2020, Andhra University, Visakhapatnam

Geotechnics of a Unique Irregular High-Rise Statue

Ravi Sundaram[1] Abhay Gupta[2] and Sanjay Gupta[1]

[1] Cengrs Geotechnica Pvt. Ltd., A-100 Sector 63 Noida-201309, India
ravi@cengrs.com, sanjay@cengrs.com
[2] Skeleton Consultants Pvt Ltd Noida-201301, India
drabhaygupta62@gmail.com

Abstract. Construction of a 107 m (351 ft) high Shiva statue on a hillock at Nathdwara, Rajasthan posed several challenges both geotechnical and structural. Detailed geotechnical investigation showed the presence of quartzite rock from the ground surface that is highly fractured at shallow depths and improves in quality with increasing depth. Rock anchors were provided for stability against wind and earthquake loading. The slopes in the surrounding areas were stabilized effectively by suitable measures. The structure details and other aspects of the elegant monument are described.

Keywords: Tallest Shiva Statue, Raft Foundation on Rock, Rock Anchors, Slope Stability.

1 Introduction

A gigantic 107-m high statue of Lord Shiva in sitting posture has recently been constructed on a 500-m high hillock at Ganesh Tekdi, Nathdwara in southwestern Rajasthan. It is the world's tallest statue of Lord Shiva and the fourth tallest statue in the world.

The base of the statue is rectangular in shape and covers an area of approximately 60m x 45m in plan area with a trident (Trishul) standing by the side. It has an irregular configuration as per IS: 1893(Part-1)-2016 [1] and has irregularity in both horizontal and vertical planes. What makes it unique is the posture & expressions which sculptor detailing has given and it imparts a divine look to the statue**.**

The paper presents results of the geotechnical and geological investigation for the statue together with the foundation system adopted along with the structural details.

2 Project Details

2.1 Conceptual Planning

The main elements for creating this monument are architecture and aesthetics of statue in the desired expressions. Structural engineering and design of main frame supporting the external shell and the design of shell are the key to a safe structure.

The site geology, geotechnical characteristics of the rock formation and slope stability are the basis of the foundation design aspects. A resourceful construction agency with rich experience and capabilities is an essential requisite to translate ideas into reality. A well-defined construction methodology for foundations, main gravity load and lateral load resisting frame, external shell skin and the statue organ shapes ensures that the statue looks gracious and elegant.
Fig. 1 presents a photograph of the statue [2] showing Lord Shiva in a pleasing appearance and the artist's impression.

Fig. 1. Photograph (left) of the 107 m (351 ft) high statue shows Lord Shiva in sitting pose with trishul by the side. Photo on the right is the sculptor's imagination (model)

2.2 Implementation Steps

Key steps in implementing the design concepts include:
1. Statue mock-up finalisation
2. Site geology and geotechnical investigations to understand the stability of hillock slopes and deciding proper foundations with ground improvement using rock anchors.
3. Posture & expressions visualisation when viewed from ground to top and body proportions done by expert sculptor.
4. In-situ concrete casting for each and every curve & cuts using full scale FRP moulds, drawn from a full scale dummy made using high density EPS and a six arm robotic CNC machine.
5. Accurate 3D modelling of continuously varying geometry and structural framing to provide stability of large cantilevers.
6. Joint-less 20000 m^2 of concrete skin casting using SCC & green cutting
7. Integration of structural steel frame and concrete skin to yield a pyramid like rigid structure to last for 250 years.

8. A 170-feet high free standing trident by side of the statue made of concrete stem and steel top.
9. Wind tunnel testing to evaluate complex wind pressure from today to whole design life including future developments.

3 General Site Conditions

3.1 Regional Geology

Geologically, Udaipur district is comprised of basement rocks of Mangalwar Complex of Bhilwara Supergroup, followed by Aravalli Supergroup, post-Aravalli intrusives, Delhi Supergroup of rocks, post-Delhi intrusives and recent alluvium [3].

The rock deposits in Nathdawara area belong to the Nathdawara Group. The formations in the area belong to the middle Proterozoic Age. It comprises phyllite, calcareous phyllite, intercalatry bands of dolomite / calcitic marble. Table 1 presents the stratigraphic succession of the Aravalis in Udaipur District [4].

Table 1. Geological Succession of the Aravali Super-group in Udaipur District.

Group	Lithology
Jharol Group	Phyllite, chlorite-schist, garnet-mica schist, calc-schist with marble, etc.
Nathdwara Group	Phyllite, calcareous phyllite, intercalatry bands of dolomite / calcitic marble.
Bari Lake Group	Meta-volcanics, conglomerate, arkose, quartzite, phyllite, schist, dolomite, quartzite etc.
Udaipur Group	Phyllite, graywacke, mica-schist, quartzite, limestone and dolomite
Debari Group	Conglomerates, arkose, quartzite, phyllite, dolomite, limestone, chert & carbonaceous phyllites, Undifferentiated granites, basic sills/ dykes

3.2 Geomorphology

Based on the general elevation, slope and landscape configuration in the terrain, the project area falls in the Aravalli landscape. The topography is hilly and undulating to semi-undulating. It experiences sub-humid to semi-arid climate and the average annual rainfall is 620-680 mm. It is mostly covered with very thin topsoil (< 0.5 m) and is underlain by rock.

The general trend of hill is N-S with inclined to steep dips. The area is traversed by numerous small to big nallas (drains). Three small prominent main seasonal nallas start from higher elevated area and merge into a downstream water pond. The general ground slope of the area is towards north east. Fig 2 is a photograph showing the site overview.

Fig. 2. Site overview

3.3 Site Conditions

The proposed project site covers an area of about 10000 m^2. It is located in hilly region approximately 500 m away from National Highway NH-8. The site is on sloping ground.

The ground rises from south to north with a level variation of about 20 m from the bottom of the hillock to the top. The general ground slope varies from 8 to 11 degrees. Some nallahs are seen in the surrounding area at lower elevation. Most of the nallahs have little or no flow except during the monsoon period.

Photographs of the site are illustrated on Fig. 3.

Fig. 3. View of site: See the rock exposed at ground level

3.4 Site Stratigraphy

The geotechnical investigation of the site included five boreholes through the rock formation. A layout plan of the site showing the locations of the boreholes is illustrated on Fig. 4.

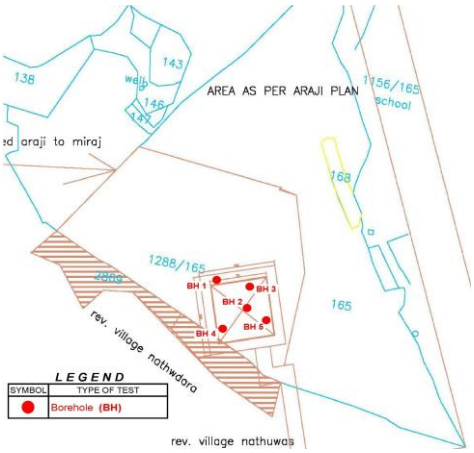

Fig. 4. Layout plan showing borehole locations

Drilling was done using NX size double tube core barrel with diamond bits. Water was circulated to lubricate and cool the bit as well as to flush out the cuttings. A photograph of the drilling in progress is illustrated on Fig. 5.

Fig. 5. Drilling in progress

Fig. 6. Typical rock cores collected

Quartzite (rock) is encountered from ground surface to the maximum explored depth of 15 m. The rock is moderately weak to strong and moderately to slightly weathered. Typical rock cores collected are illustrated on Fig. 6.

In general, the rock at shallow depth to about 1.5-4 m depth (RL 79-84.5 m) is weak and highly fractured and has iron stains. Core recoveries in this zone range from 0 to 28 percent and the RQD value ranges from 0 to 10 percent.

Below this, the fracture frequency reduces somewhat to about RL 78 to RL 70 m. Reddish brown iron stains / veins are observed in the rock mass. Core recoveries in this zone range from 40 to 90 percent and the RQD value ranges from 33 to 50 percent. Fig. 7 presents typical boreholes drilled.

The rock below RL 78-70 m is strong and slightly weathered. The joints are widely spaced. Core recoveries in this zone range from 52 to 95 percent and the RQD value ranges from 56 to 87 percent.

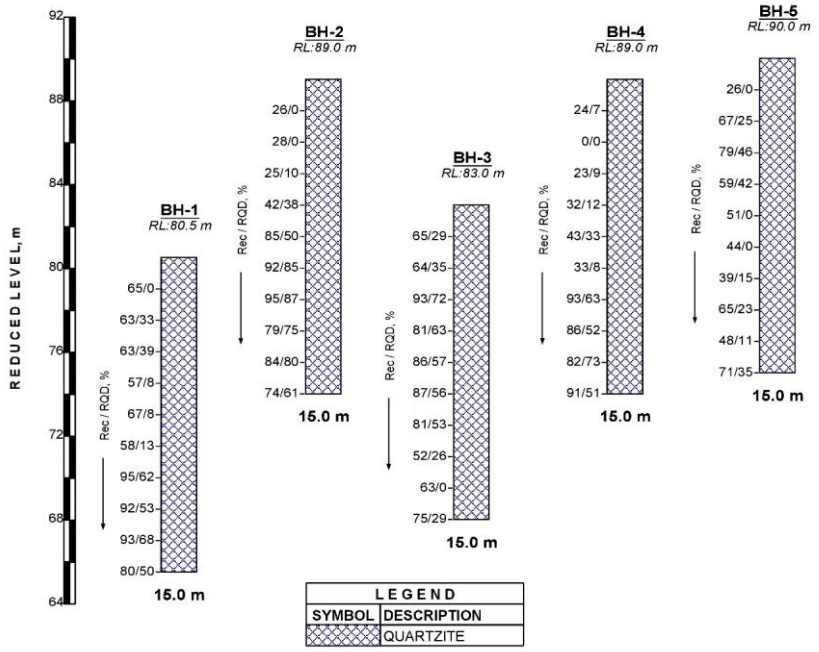

Fig. 7. Typical boreholes profile

3.5 Assessment of Slope Stability

In general, the hill slopes at the project site are fairly stable. The slopes within the plot and surrounding areas are not steeper than 8 to 11 degrees. Further, rock is exposed at the ground surface all over the area. Hence, slope failure in slip-circle mode of failure is unlikely to occur. No zones of rock blocks that may get dislodged are seen. Below 3-4 m depth, the rock mass has widely spaced joints. Hence, block failure of the rock mass is unlikely.

4 Foundation Analysis

4.1 Foundation Type and Bearing Capacity

RCC raft foundation with raised pedestals to support the statue was cast at 4m depth. Bearing capacity analysis was done as per IS: 12070-1987 RA 2010 [5]. Based on assessment of RMR of the rock mass and the crushing strength of the rock, the raft was designed for a net allowable bearing pressure of 700 KN/m^2.

A photograph showing the foundation level prepared for raft construction is illustrated on Fig. 8. Fig. 9 shows the pedestals constructed over the raft.

Fig. 8. Foundation level preparation

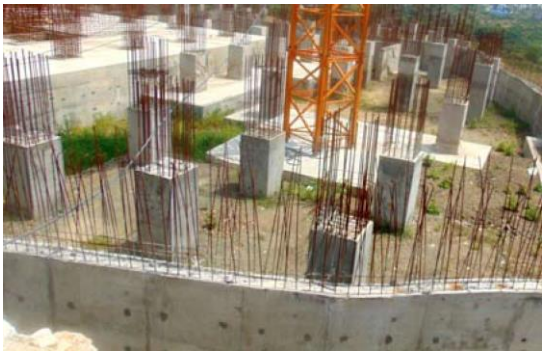

Fig. 9. Foundation construction in progress

4.2 Rock Anchors

For long term stability of the statue and for stability against wind and earthquake loading, rock anchors were provided. The basic wind speed for the structure has been taken 47 m/s (IS: 875 Part 3-2015 [6]) and wind pressure is calculated for various heights for Statue & Trishul for a design wind speed of 70 m/s. As per IS: 1893 (Part1)-20016 [1], design was done considering the following parameters:

- Earthquake Seismic Zone : IV
- Importance factor of the structure : 2
- Response reduction factor : 3
- Damping ratio : 2%.

Rock anchors, 8m long, embedded 7m into the rock and 1m into the raft were provided. The anchors were installed in 100mm diameter drilled holes with a Fe500 32mm TMT reinforcement bar grouted into the rock. Grouting was done using a GP-2 non-shrink grout. Anchors were designed to resist the entire lateral force due to wind and earthquake, ignoring the frictional resistance between rocks and concrete. The anchors were placed all along the periphery of concrete wall forming the hillock at the

base of statue. A drawing showing anchor layout and other details is illustrated on Fig. 10.

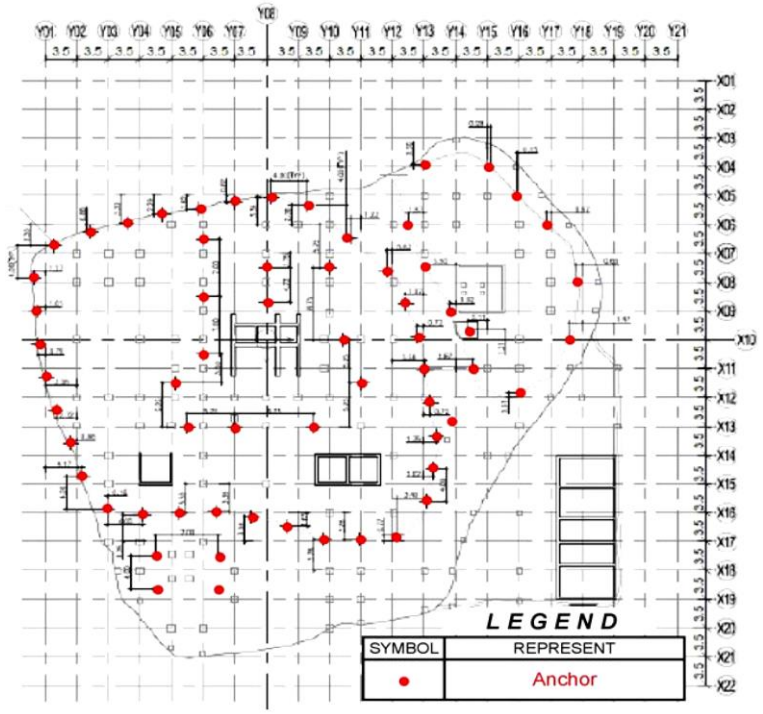

Fig. 10. Anchors Layout

4.3 Slope Protection Measures

For long term stability of slopes around the site slope protection measures were adopted:

1. Proper drainage has been provided for the site roads.
2. Shoulder drains have been provided on either side of the roads and the water is drained away into carefully selected drainage ditches for disposal.
3. In areas where rock slopes have been excavated and adequate precautions have been taken to ensure that the slope is stable.
4. A concrete paving has been provided all around the outer perimeter of the proposed structure. This pavement extends 1.5m beyond the outer edge of the exterior foundations. The paving helps in limiting water ingress into the soils beneath the foundations.
5. Entire base of statue has been provided with 8-m deep HYSD bars anchoring rocks for 7m penetration and 1m inside the raft foundation. This will help binding the rocks as well as stability to entire structure.

4.4 Structure Details

The monument classifies as an irregular structure as per IS: 1893 (Part 1)-2016 [1]. The irregularity lies in both horizontal and vertical planes. So, steel members designed as per IS: 800-2007 [7] were used to provide flexibility of configuration and behavior as well as ease of construction.

There is a huge platform representing seat for the Lord of about 33m (110 ft) height over which Lord Shiva is sitting. The internal space has a lift and a staircase system for maintenance and monitoring purpose. Some internal floors are for common public use and a museum.

External skin of the statue was made through in-situ concrete pouring in specially made glass-fibre moulds. To properly support this skin and to transfer the wind forces / self-weight, special non-corrosive connections were designed. The thickness of skin shell varied from 200mm to 400mm. External geometry of statue at every 3m interval has been used to prepare structural framing by superimposing all floor plans and arranging RCC walls designed as per IS: 456-2000 [8] & steel columns which can be taken through to maximum possible heights.

Fig. 11 presents the statue under construction. Fig. 12 presents the fully constructed statue and the development around it depicting Lord Shiva majestically overseeing and benevolently ruling over the surroundings.

Fig. 11. Construction in progress

Fig. 12. View of the statue & surroundings

5 Conclusions

The statue is a culmination of the efforts by geotechnical engineer, structural designer, sculptor, project managers and the construction agency. In addition to the geotechnical investigation, it involved installing about 70 rock anchors, 2600 tonnes of structural steel, casting about 13000 m^3 of concrete and 20000 m^2 of concrete skin.

Acknowledgement

The authors are extremely grateful to the Miraj Group of Industries, Nathdwara who developed this statue at Nathdwara for giving them an opportunity to be a part of this grand and mammoth project. M/s. Cengrs Geotechnica Pvt. Ltd. performed the geotechnical investigation and M/s. Skeleton Consultants have done the structural analysis and design as well as the wind tunnel testing. Prof Prem Krishna, former professor IIT Roorkee did the proof checking of design. M/s Shapoorjee Pallonjee Constructions did the execution. The project has received several awards so far for excellence in design & construction.

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